NASA Technical Memorandum 107162

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May 1996

National Aeronautics and
Space Administration

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SUMMARY

The shear strength of an aluminum/ice adhesive bond is analyzed for the purpose of gaining an appreciation for the forces necessary to break this bond. The results of this work have a direct bearing on future attempts to develop de-icing systems for aircraft. Results of testing indicate that system temperature, bonding surface conditions, and ice purity profoundly influence the adhesion strength. An explanation of testing parameters and procedures are presented, along with a detailed characterization of the results and suggestions for further study.

INTRODUCTION

The problem of aircraft icing is almost as old as the aerospace industry itself. As an aircraft flies through clouds, super-cooled droplets of water can collect on the surface and freeze. As this ice accumulates, flow over critical control surfaces can be interrupted, inducing stalls and causing loss of control of the aircraft.

Most early work in aircraft icing focused on cataloging the types of conditions necessary to generate these "icing conditions." From this data, deicing and anti-icing systems were developed. Unfortunately, these systems, while very effective, are much too expensive for the general aviation community.

Other systems are being developed that may provide an answer for this large, unprotected market. Some of these new systems will apply an impulse force or vibration to break the ice. However, the force necessary to accomplish this depends on the adhesive strength of the ice to the metal surface (skin) of the aircraft.

Little research has been performed to measure such strength. Thus, it is necessary to closely examine this bond before proceeding with the development of a system to break it.

GOALS

The goal of this exercise was to use a static test to determine the adhesive shear strength of the aluminum/ice bond, simulating, as closely as possible, actual flight conditions. Also, this exercise was to examine how this strength is affected by surface conditions, ice purity, and temperature.

PROCEDURE

In understanding the rationale of this procedure, it is first necessary to understand the overriding goal of this exercise. While laboratory, ideal-condition results are important, the goal of this experiment, that of obtaining the stresses necessary to deice aircraft, dictates a procedure geared more towards simulating realistic flight situations.

The first step of this study was the selection of an appropriate metal for the adhesion tests. Due to time constraints on this experiment, only one metal could be tested. As mentioned in the GOALS section, aluminum was selected for examination, mainly because of its wide application to aircraft skin design.

Samples of aluminum cylindrical rods with a diameter 0.5 inches and a

length of 3.5 inches were used in the testing. At one end, the rods were modified to allow for a quick connect/disconnect to the tensile tester. The surfaces of the aluminum rods were modified, to reflect the intent of producing tests mirroring actual aircraft conditions. One set of aluminum rods (specimens) was maintained as a smooth surface, simulating the skin conditions of a new airplane. The next set of specimens was scratched and dented, simulating aircraft skin after many hours of exposure to the hostile flight environment. Finally, the third set of rods was coated with aircraft paint.

After the aluminum specimens were modified, the levels of ice purity were chosen. The choice was difficult, as an aircraft can encounter many different ice purities, depending on its particular situation. Thus, in keeping with the goal of simulating actual conditions, a flight envelope was created to include all possible situations. At one extreme, distilled water represented the purest form of water that a craft could possibly encounter. At the other extreme, water samples were taken directly from Lake Erie. Finally, rain water was collected at the NASA Lewis Research Center. This rain water most closely approximated the typical degree of water purity encountered by an aircraft.

A chart explaining the parameters of the test is given in Table 1. Each of these tests were performed at each 10°F increment from -10°F to 20°F, thereby examining the effect of all three test variables (temperature, surface conditions, and ice purity).

The preparation of the specimens also reflected efforts to maintain actual flight conditions. First, the cleaned specimens were placed in a freezer (with temperature accuracy +-3°F) and reduced to testing temperature. Likewise, the water sample was placed in a styrofoam cup and brought to near-

freezing temperature. This closely mirrors the process by which water bonds to the colder aircraft surface, then freezes. After achieving the appropriate temperatures, the specimens were combined and reduced to testing temperature.

After the test specimen reached the correct temperature, the aluminum rod was checked for perpendicularity to the ice surface (necessary to ensure only shear forces were applied to the system), and the styrofoam was removed from the ice. A typical specimen is shown in Figure 1.

The mount of the tensile tester required modification in order to apply shear forces. A steel cage was fabricated for this purpose. Mounted to the base of the tester, it encapsulated a test specimen, applying a shear force when the system was raised. The mount and a typical test specimen are shown in Figure 2.

Unfortunately, the tensile tester could not be placed in a freezer, due to its physical dimensions. As a result, all testing was performed at room temperature (about 70°F). To prevent quick warming or melting, which would invalidate results, a few additional features were included in the testing system. First, the aforementioned quick connection allowed for tests to be completed, from freezer to fracture, in under 40 seconds. In addition, a metal washer, also reduced to testing temperature, was placed over the top surface of the ice. This had two desirable consequences. First, it prevented premature melting due to contact between the ice and steel cage test mount. Second, it provided a smooth, even force over the ice that formed the bonding surface. These two additional measures prevented undesired warming and melting during the brief testing period, assuring accurate data points despite the drastic difference between testing and room temperature.

Once the specimen was on the mount, as in Figure 3, the tensile tester applied a shear force to the bonding surface by raising the specimen at a rate

of 1 inch/minute. This rate was chosen because it was the slowest rate which did not produce significant melting during the test. The surface adhesion broke down, and the maximum force required for this fracture was recorded. Then, knowing the required force and the surface area of the bond, the shear strength of the bond could be found using equation one:

$$\sigma = Strength = \frac{Force}{Area} \tag{1}$$

An important point about testing with ice is given in ref. 1. It warns that large degrees of scatter result from testing with ice. This is due to the manner in which the ice forms, etc. Thus, repetition was very important to this procedure. 10-15 tests were typically needed to provide statistical confidence to each data point.

RESULTS

Unfortunately, the tensile tester used for this study was damaged during the testing period. This damage was severe enough to force the cancellation of all remaining tests. As a result, tests involving the third ice purity (made from rain water) and third surface modification (painted) could not be performed.

Despite this setback, tests were completed for smooth and scratched surfaces in distilled and lake water purities. These surfaces give an adequate approximation of an unpainted aluminum surface for the lifetime of an aircraft. The purities establish an envelope for the many potential ice purities an aircraft could encounter. Thus, while not all of the desired tests were completed, the ones that were finished provided an excellent appreciation of the trends and values of the bond's shear strength. Tabulated results are found in Appendices A and B.

The first variable examined in this experiment was the effect of temperature on bond shear strength. For each surface and ice purity, approximately 10-15 tests were made at each 10°F increment from -10°F to 20°F. This variable was more challenging than the others, as it was more difficult to ensure accurate test temperatures than to control the other two variables. However, the measures outlined in the Procedure provided adequate protection to keep the specimen test temperature variance within the experimental error of the refrigerator.

At 20°F, the aluminum/ice bond was broken for almost every trial. That is, for these tests, the aluminum was pulled cleanly from the ice. However, at 10°F, small ice chunks remained on the surface after fracture. Below 10°F, ice chunks covered the aluminum surface after it had separated from the main ice specimen.

This result supports the conclusions of the experiment described in ref. 2. At lower temperatures, the aluminum/ice bond becomes stronger than the crystalline structure of the ice itself. As a result, any force applied to the system will crack the ice before breaking its bond to aluminum. Thus, the only conclusion that can be drawn regarding the effect of temperature is that at colder test temperatures, the bond is <u>at least</u> as strong as the crystalline structure of the ice.

The next variable examined in this experiment is the effect of surface conditions on the bond. At higher temperatures, this variable is quite important. As seen in Figures 4 and 5, the average scratched surface bond strength is greater at these temperatures than its smooth counterpart, independent of ice purity. As the temperatures are reduced, the difference becomes inconsequential.

Another important distinction between scratched and smooth surfaces was

found at lower temperatures after fracture. That is, the ice that remained bonded to the surface had a different appearance depending on the surface condition. The smooth surface had a very thin, smooth surface of ice bonded to it, while the scratched surface had a thicker, chunky surface of ice.

These distinctions relate very strong information about the bond surface. The scratched surface bond is stronger at warm temperatures because the area of the bond slightly increases, as ice freezes along every exposed surface of the aluminum. At the lower selected test temperatures, the crystalline structure of the ice breaks before the bond. Thus, surface conditions decrease in importance. Also, the change in type of ice on the surface indicates that the crystalline structure of the ice is different at the two surfaces. It is possible that the altered crystalline structure near the scratched surface helps to fortify the bond. As the temperature is reduced, the crystalline structure of the ice shatters at about the same stress, independent of surface conditions.

The final variable examined in this experiment is the effect of ice purity on the aluminum/ice bond. The averaged results of this effort are shown in Figures 6 and 7.

For both surfaces, the difference between lake and distilled ice is minimal for warmer test temperatures. However, below 10°F, the bond strength of the distilled ice decreases or remains nearly constant, while the lake ice bond strength increases sharply.

This trend difference is due to the condition of the ice. As stated in ref. 2, at colder temperatures, the failure, in the ice structure, "is brittle and depends on the propagation of cracks." When the distilled water froze, there were many cracks and imperfections in every specimen. However, the lake water, selected for its impurities, was surprisingly clear and contained very

few cracks.

These cracks had a profound influence on the shear strength. The distilled ice fractured quite readily, no doubt in part to the pre-formed cracks in the ice. The lake ice held its form and its hold on the aluminum through a much higher stress, as it had no pre-formed cracks to aid in yielding.

In examining the numbers associated with these results, it is important to keep in mind the problem of data scatter associated with this testing. Figures 8-11 show plots from this experiment, along with error bars determined to 90% confidence. The mean and standard deviation (SD) for each point can also be seen in Appendix B. One must consider this scatter in choosing a factor of safety when designing a deicing system using this data.

CONCLUSIONS AND RECOMMENDATIONS

This research is merely the first step in truly understanding the bond between ice and aircraft surfaces such as aluminum. However, it provides an excellent starting point in this quest. It showed that surface conditions, ice purity, and temperature all profoundly affected the strength of the bond:

1. At lower test temperatures, the bond strength between the aluminum and ice exceeds that of the crystalline structure of the ice itself.

2. At higher test temperatures, the scratched surface of the aluminum resulted in a slightly stronger bond than the smooth surface. At lower temperatures, surface differences decreased in importance.

3. At lower temperatures, impurities in the ice profoundly increased the shear strength of the bond.

Also, this experiment emphasized the importance of avoiding idealization for the development of deicing systems. Imperfections and impurities not considered can actually strengthen the aluminum/ice bond, and an ideal deicing system could be underdesigned for flight conditions.

This research will hopefully provide a foundation for further efforts. Continued testing of the systems examined will help to further reduce the error associated with this testing, as well as verify the bond characterizations provided in this report. In addition, other systems should be considered. These include additional surface modifications, ice purities, strain rates, and even different metals, as aircraft surfaces are no longer limited to aluminum.

REFERENCES

[1]Peter V. Hobbs. Ice Physics. Oxford: Clarendon Press, 1974.

[2]L.E. Raraty and D. Tabor. "The adhesion and strength properties of ice." 1957.

	Distilled Water	Lake Water	Rain Water
Smooth Surface	X	X	X
Scratched Surface	X	X	X
Painted Surface	X	X	X

Table 1 - Test Matrix

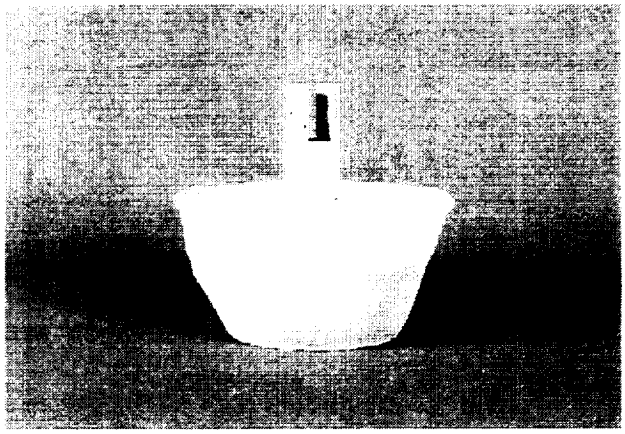

Figure 1 - Aluminum specimen frozen in ice

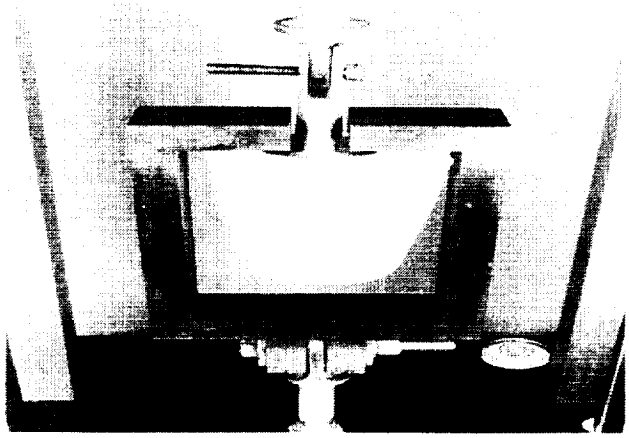

Figure 2 - U-Shaped Base Mount with Test Fixture

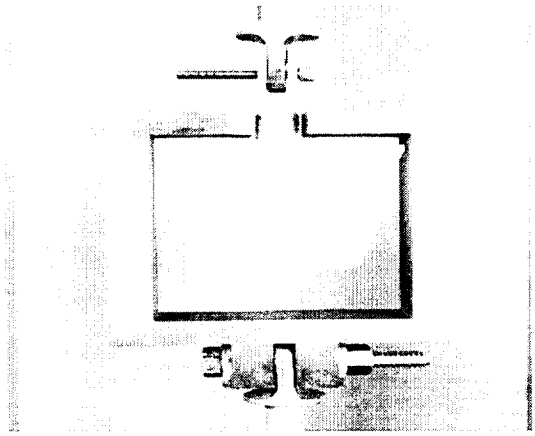

Figure 3 - Specimen in test mount. Notice the metal washer on the top surface of the ice which provides and even force over the bonding surface and prevents premature warming.

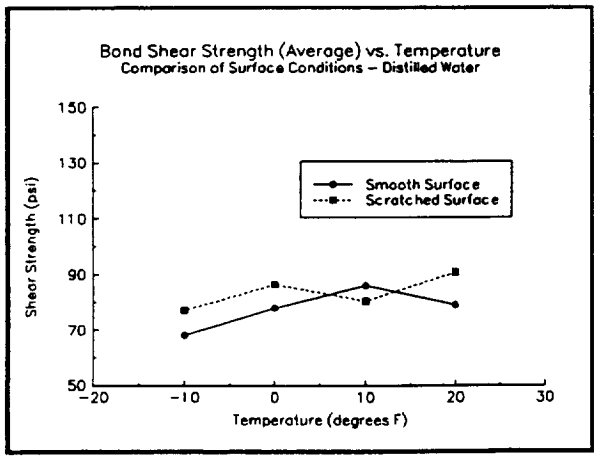

Figure 4

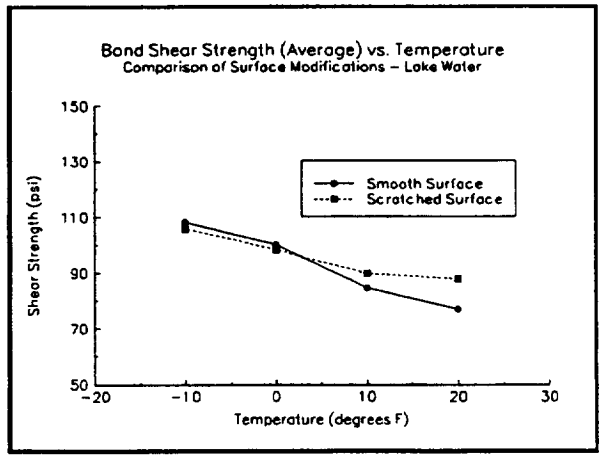

Figure 5

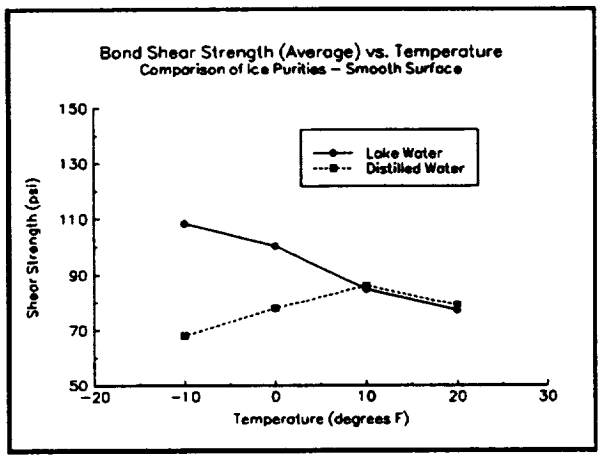

Figure 6

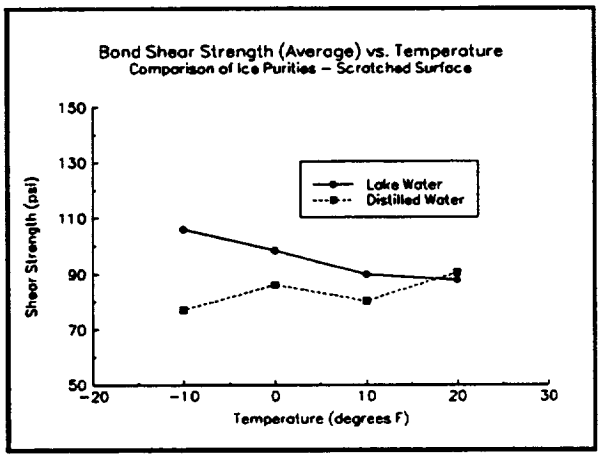

Figure 7

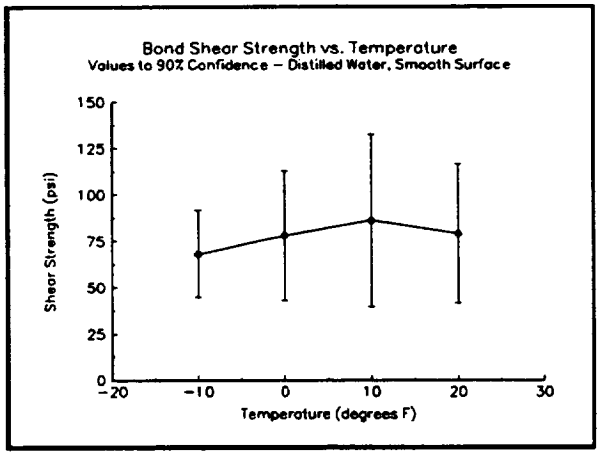

Figure 8

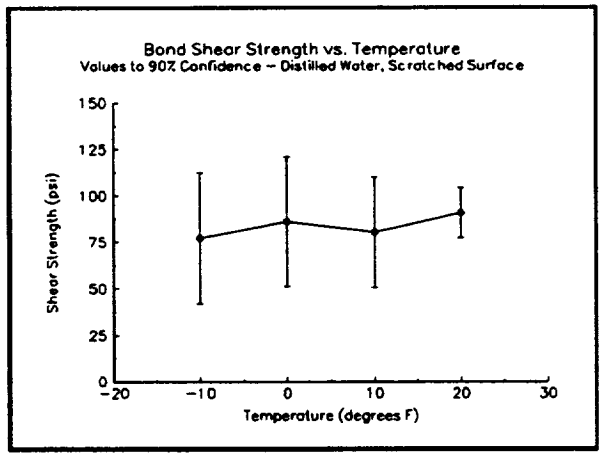

Figure 9

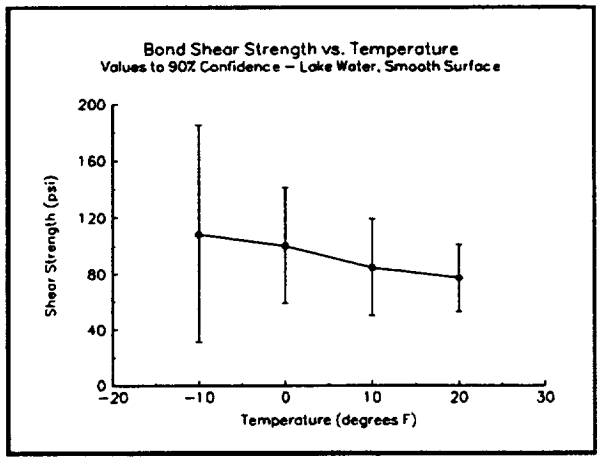

Figure 10

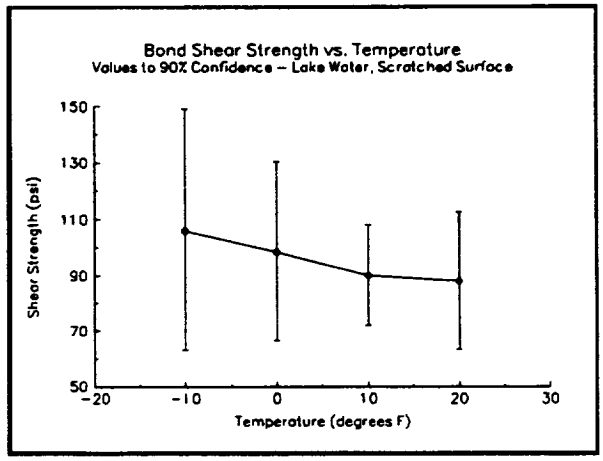

Figure 11

APPENDIX A

Daily Test Log

Ice/Aluminum Bond Tests - 6/14/95

Temperature - 20°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
1	Tap	Unalt.	1	293.0	0.023	2.4375	0.55
2	Tap	Unalt.	2	316.5	0.029	2.375	1.00
3	Tap	Unalt.	3	351.0	0.049	2.5625	1.00
4	Tap	Unalt.	4	-----	-----	-----	-----
5	Pure	Smooth	1	294.1	0.040	2.125	1.00
6	Pure	Smooth	2	332.5	0.035	2.4688	1.00
7	Pure	Smooth	3	279.6	0.043	2.25	1.00
8	Pure	Smooth	4	210.6*	0.025*	2.4375	1.00

Notes (refer to Test #)

1
- Severe melting over contact surface - Req. Faster speed for normal testing

2
- Stopped Tare Late (Questionable results)
- Sample not squared with ice
- Melting after fracture (Speed OK)

3
- Small fragments left on b.s. (vertical stripes of greater/lesser thickness)

4
- NOT CENTERED - UNUSABLE

5
- Large cracks in radial plane - 0.5in. from b.s. at closest approach (2 cracks connecting)
- Fracture allowing release went into these at closest point

6
- Many more cracks, some reaching bonding surface

7
- Not as much cracks as (6)
- 0.5in. radius around b.s. - air pockets/cracks radially outward from b.s.
- Fracture travels in same direction

*8
- Large crack through b.s. from one side of ice to other - UNUSABLE
- Clean breakaway!

Ice/Aluminum Bond Tests - 6/15/95

Temperature - 20°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
9	Pure	Scratch	1	351	0.034	2.4375	1.00
10	Pure	Scratch	2	-----	-----	-----	-----
11	Pure	Scratch	3	273.3	0.046	1.9375	1.00
12	Pure	Scratch	4	351	0.057	2.40625	1.00
13	Pure	Smooth	4	210.4	0.022	2.375	1.00
14	Pure	Smooth	5	449	0.047	2.375	1.00
15	Pure	Smooth	6	294.4	0.036	2.5	0.28

Notes (refer to Test #)

9
- Loud vibration coming from sample after fracture
- More stress lines on ice before test (same for all samples today)

10
- NOT CENTERED - UNUSABLE

11
- Small chunks of ice remained on specimen near bottom of b.s.
- Not pushed to bottom of cup - Normal forces?

12
- Chunks on surface

13
- Repeatability problem - Do we need a slower speed?

14
- Ice cracked near b.s. at top
- Loud vibration noise again
- Thin sheet of ice on b.s. starting 3/4" from top of b.s.

15
- Comparable results yielded - remain with speed setting to avoid melting

Ice/Aluminum Bond Tests - 6/16/95
Morning Tests

Temperature - 20°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
16	Pure	Scratch	5	351	0.032	2.1875	1.00
17	Pure	Scratch	6	320.1	0.033	2.3125	1.00

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
18	Pure	Scratch	1	-----	-----	-----	-----
19	Pure	Scratch	2	-----	-----	-----	-----
20	Pure	Smooth	1	441	0.043	2.3125	1.00
21	Pure	Smooth	2	-----	-----	-----	-----
22	Pure	Smooth	3	229.9	0.034	2.4375	1.00
23	Pure	Smooth	4	339.2	0.050	2.375	1.00

Notes (refer to Test #)

16
- Loud noise from specimen after fracture

17
- Two large cracks across diameter of ice <0.25in. at closest approach

18
- Very uneven surface of ice forced specimen sideways - UNUSABLE

19
- Not centered and surface froze unevenly - UNUSABLE

20
- Air bubbles same distance from specimen at 20°F, but thicker section (goes farther out radially)
- Large section of ice still attached (ring around specimen) located 3/8in. down from top of ice to 7/8in. down

21
- Uneven ice surface - UNUSABLE

22
- Conditions similar to Test #20

23
- Smaller bubble area than Tests #20 & #22, but same radius from specimen
- Loud noise from specimen after fracture

Ice/Aluminum Bond Tests - 6/19/95
Morning Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
24	Pure	Scratch	3	-----	-----	-----	-----
25	Pure	Scratch	4	500	0.099*	2.375	1.00
26	Pure	Scratch	5	248.4	0.043	2.3125	1.00
27	Pure	Scratch	6	-----	-----	-----	-----
28	Pure	Smooth	5	210.5	0.092	1.875	1.00
29	Pure	Smooth	6	176.3	0.074	1.875	1.00
30	Pure	Smooth	7	-----	-----	-----	-----
31	Pure	Smooth	8	167.4	0.030	1.625	1.00

Notes (refer to Test #)

24
- Noticeably little water in sample (problem throughout test session)
- Cracked around surface in hexagonal pattern (1/4in. from sample)
- Uneven surface - UNUSABLE

25
- Small bump in ice at surface - Displacement value off

26
- Very few visible cracks, but 'wavy surface'

27
- Large crack across diameter of ice 3/8in. from sample
- Break sideways - UNUSABLE

28
- 2 Large cracks across ice diameter 1/4in. from surface
- Debatable whether or not results are valid, although sample was pulled out vertically (no noticeable horizontal movement)

29
- Slight break sideways - Unusable?

30
- Large crack across ice diameter 1/2in. from surface
- Ice cracks yielded UNRELIABLE results

31
- Many cracks across ice, but all greater than 3/8in. from b.s.
- Again, ice fractured easily, yielding QUESTIONABLE results

Ice/Aluminum Bond Tests - 6/19/95
Afternoon Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp	Height	Speed
32	Pure	Scratch	7	351	0.051	2.625	1.00
33	Pure	Scratch	8	347.1	0.059	2.625	1.00
34	Pure	Scratch	9	347.3	0.060	2.625	1.00
35	Pure	Scratch	10	262.7	0.045	2.625	1.00

Temperature - 0°F

Test	Water	Sample	#	Force	Disp	Height	Speed
36	Pure	Smooth	1	292.2	0.040	2.6875	1.00
37	Pure	Smooth	2	293.2	0.044	2.6875	1.00
38	Pure	Smooth	3	351	0.036	2.75	1.00
39	Pure	Smooth	4	276.1	0.042	2.6875	1.00

Notes (refer to Test #)

32
- Good specimen; bubble ring at same distance

33
- Large crack less than 1/4in. from b.s.

34
- Large crack 3/8in. from b.s.
- Loud rumbling noise coming from test after fracture
- With fracture, major cracks across ice

35
- Major cracks, but all greater than 1/2in. from ice
- Lower volume rumbling noise after fracture
- Uneven surface, possible error in measure (although small)

36
- Major cracks across ice diameter reaching b.s. tangentially
- Ice chunks on specimen after fracture at top of b.s.

37
- Major cracks across ice diameter 3/8in. from b.s.
- With fracture, more cracks throughout ice
- Ice chunks again, even larger (1/2in. down from top of b.s.)

38
- Ice uneven (chunks raised above surface)
- Loud noise after fracture
- Large chunks remain on b.s. (greater than 5/8in. in length, 1/2in. down from top of b.s.)

39
- No unusual traits (no large cracks)

Ice/Aluminum Bond Tests - 6/20/95
Morning Tests

Temperature - 0°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
40	Pure	Scratch	1	-----	-----	-----	-----
41	Pure	Scratch	2	351	0.034	2.3125	1.00
42	Pure	Scratch	3	351	0.108	2.75	1.00
43	Pure	Scratch	4	450	0.034	2.5	1.00
44	Pure	Smooth	5	285.5	0.039	2.6875	1.00
45	Pure	Smooth	6	351	0.032	2.625	1.00

Temperature - -10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
46	Pure	Smooth	1	338.2	0.033	2.5625	1.00
47	Pure	Smooth	2	296.1	0.029	2.5	1.00

Notes (refer to Test #)

40
- Frozen sideways - unusable

41
- Major crack across ice 1/4in. from b.s.
- Ice fracture before b.s. fracture

42
- Ice fracture before b.s. fracture

43
- Major crack across ice 1/4in. from b.s.

44
- Major crack across ice 3/8in. from b.s.
- Large chunks of ice on b.s. after fracture

45
- No noteworthy comments

46
- Ice very foggy - difficult to see
- Ice fracture instead of b.s. fracture

47
- Ice chipping on fracture
- Some pieces remain on b.s. at the top of the surface

Ice/Aluminum Bond Tests - 6/20/95
Afternoon Tests

Temperature - 0°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
48	Pure	Scratch	5	-----	-----	-----	-----
49	Pure	Scratch	6	351	0.037	2.375	1.00
50	Pure	Scratch	7	242.7	0.032	2.5	1.00

Temperature - -10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
51	Pure	Scratch	1	250.2	0.034	2.5	1.00
52	Pure	Smooth	3	351	0.028	2.5625	1.00
53	Pure	Smooth	4	260.5	0.035	2.5	1.00
54	Pure	Smooth	5	201.6	0.029	2.5625	1.00
55	Pure	Smooth	6	198.6	0.029	2.375	1.00

Notes (Refer to Test #)

48
- Not frozen - UNUSABLE

49
- Some traces of ice on b.s. after fracture

50
- Chunks of ice remained on surface
    - indicates definite ice fracture, not b.s. separation

51
- Ice shatter at fracture

52
- Fracture in ice
- Chunks of ice remain on specimen

53
- Slow crack through ice (delayed fracture - snapping sounds)

54
- Crack in ice
- Test ended quickly (no residual force upon fracture)

55
- Ice sent flying at fracture - indicates ice breaking before b.s.

Ice/Aluminum Bond Tests - 6/21/95
Morning Tests

Temperature - -10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
56	Pure	Scratch	2	171.6	0.059	2.375	1.00
57	Pure	Scratch	3	304.1	0.059	2 5/16	1.00
58	Pure	Scratch	4	209.4	0.045	2 7/16	1.00
59	Pure	Scratch	5	247.7	0.060	2 5/16	1.00
60	Pure	Smooth	7	256.6	0.027	2 9/16	1.00
61	Pure	Smooth	8	192.9	0.057	2 7/16	1.00
62	Pure	Smooth	9	261.7	0.031	2.25	1.00
63	Pure	Smooth	10	127.0	0.039	2.5	1.00

Notes (refer to Test #)

56
- Break sideways - QUESTIONABLE results
- Ice Fracture and chipping upon fracture

57
- Ice fracture before max. force
- Ice chunks on specimen
- Ice chipping upon fracture

58
- Ice uneven
- Ice fracture, followed by max. force, then b.s. fracture of remaining ice
- Ice breaks before bond

59
- Again, ice fracture before b.s. fracture

60
- Ice fractures in 1/2 (like others), then b.s. fractures later
- Max force fractures the ice

61
- Ice formed unevenly at surface
- B.S. not separating - ice is fracturing first!

62
- Ice fractures before b.s.

63
- Same as previous samples
- Broke sideways - QUESTIONABLE results

Ice/Aluminum Bond Tests - 6/22/95
Morning Tests

Temperature - 20°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
64	Lake	Scratch	1	351	0.031	2.40625	1.00
65	Lake	Scratch	2	-----	-----	-----	-----
66	Lake	Scratch	3	445	0.041	2.5625	1.00
67	Lake	Scratch	4	351	0.034	2.53125	1.00
68	Lake	Smooth	1	310.5	0.036	2.625	1.00
69	Lake	Smooth	2	228.7	0.028	2.625	1.00
70	Lake	Smooth	3	401	0.033	2.625	1.00
71	Lake	Smooth	4	-----	-----	-----	-----

Notes (refer to Test #)

64
- Uncracked ice!
- Small cracks at fracture
- Moaning sound after fracture (but not immediately after)

65
- No cracks, but small surface imperfections
- Error in test procedure - UNUSABLE

66
- A little ice left on b.s. after fracture

67
- No ice left on b.s.

68
- Unblemished ice
- Load moaning from specimen after fracture

69
- Nothing significant
- Smooth surfaces coming out completely clean!

70
- Small crack across ice surface greater than 3/8in. from b.s.
- Quick test end after fracture (no residual forces)

71
- Frozen sideways - UNUSABLE

Ice/Aluminum Bond Tests - 6/22/95
Afternoon Tests

Temperature - 20°F

Tests	Water	Sample	#	Force	Disp.	Height	Speed
72	Lake	Scratch	5	270.0	0.042	2.5	1.00
73	Lake	Scratch	6	-----	-----	-----	-----
74	Lake	Smooth	5	279.7	0.033	2.625	1.00
75	Lake	Smooth	6	253.2	0.034	2.46875	1.00

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
76	Lake	Scratch	1	351	0.028	2.46875	1.00
77	Lake	Scratch	2	351	0.037	2.5	1.00
78	Lake	Smooth	1	351	0.031	2.375	1.00
79	Lake	Smooth	2	276.6	0.040	2.4375	1.00

Notes (refer to Test #)

72
- Ice chunks on surface after fracture

73
- Major crack 1/2in. from b.s.
- Not frozen adequately - UNUSABLE

74
- Large crack 3/8in. from b.s.
- Loud moaning sound coming from specimen after fracture

75
- Came out after fracture with no ice chunks
- Test ended quickly - low residual forces

76
- Cracks through ice as force applied
- Some ice chunks on specimen after fracture

77
- Cracks through ice as force applied
- Ice chunks on specimen

78
- Loud moaning/cracking sound after fracture
- Ice chunks on specimen

79
- Loud moaning after fracture
- Slight sideways motion - QUESTIONABLE results

Ice/Aluminum Bond Tests - 6/23/95
Morning Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
80	Pure	Scratch	11	272.3	0.037	2.25	1.00
81	Pure	Scratch	12	306.9	0.060	2.375	1.00
82	Pure	Scratch	13	204.4	0.032	2.4375	1.00
83	Pure	Scratch	14	286.3	0.023	2.625	1.00
84	Pure	Smooth	9	276.9	0.035	2.5625	1.00
85	Pure	Smooth	10	284.9	0.031	2.4375	1.00
86	Pure	Smooth	11	334.0	0.036	2.4375	1.00
87	Pure	Smooth	12	258.1	0.041	2.375	1.00

Notes (Refer to Test #)

80
- Ice chunks on specimen after fracture
- Cracking sounds continue after fracture

81
- Major ice cracks at fracture point
- Little residual force after fracture
- Some ice chunks on specimen

82
- One side of ice broke, then the other
- Ice fracture, followed by b.s. breakdown?

83
- Ice chunks on specimen after fracture

84
- Ice chipping after fracture
- Moaning sound coming from specimen after fracture
- Ice remains on b.s.

85
- Moaning sound briefly after fracture, then returns loudly later
- Ice remains on b.s. (Smoother with smooth surface, like a "sheet")

86
- Moaning sound again

87
- Moaning again
- Little residual forces after fracture

Ice/Aluminum Bond Tests - 6/23/95
Afternoon Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
88	Lake	Smooth	3	292.6	0.050	2.375	1.00
89	Lake	Smooth	4	260.4	0.033	2.375	1.00
90	Lake	Smooth	5	502	0.049	2.4375	1.00
91	Lake	Scratch	3	-----	-----	-----	-----
92	Lake	Scratch	4	351	0.044	2.5	1.00
93	Lake	Scratch	5	351	0.045	2.375	1.00
94	Pure	Scratch	15	278.1	0.027	2.625	1.00
95	Pure	Smooth	13	-----	-----	-----	-----

Notes (refer to Test #)

88
- Load moaning sound after fracture
- "Sheet" ice around surface

89
- "Sheet" ice around b.s.

90
- Loud moaning from specimen after fracture
- "Sheet" ice around b.s.

91
- Not frozen - UNUSABLE

92
- No moaning sound
- Ice chunks on specimen

93
- No moaning sound
- Ice chunks on specimen

94
- Slight moan at fracture
- Not frozen - QUESTIONABLE results

95
- Froze sideways - UNUSABLE

Ice/Aluminum Bond Tests - 6/26/95
Morning Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
96	Pure	Smooth	14	582	0.049	2.5	1.00
97	Pure	Smooth	15	252.3	0.047	2.0625	1.00
98	Pure	Smooth	16	288.5	0.040	2.3125	1.00
99	Pure	Smooth	17	183.4	0.032	2.625	1.00
100	Pure	Scratch	16	347.2	0.046	2.375	1.00
101	Pure	Scratch	17	295.1	0.038	2.5	1.00
102	Pure	Scratch	18	479	0.049	2.3125	1.00
103	Lake	Scratch	7	304.1	0.030	2.25	1.00

Notes (refer to Test #)

96
- Ice cracks on fracture

97
- Cracking noises after fracture
- Ice chunks on b.s.

98
- Moaning, then squeaking, then moaning sound after fracture
- Ice chunks on surface

99
- Long period of cracking after fracture
- Overall test ended quickly

100
- Ice chunks on b.s. after fracture
- More residual forces then all smooth tests this morning

101
- Ice chipping on fracture
- Again, more residual forces
- Ice chunks on surface

102
- Some residual forces
- Ice chunks on b.s. ("sheet" form - normally seen on smooth surface)

103
- Major chunks on b.s. after fracture

Ice/Aluminum Bond Tests - 6/26/95
Afternoon Tests

Temperature - 0°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
104	Lake	Smooth	4	-----	-----	-----	-----
105	Pure	Scratch	8	311.7	0.072	2.5625	1.00
106	Pure	Scratch	9	299.6	0.054	2.5625	1.00
107	Pure	Scratch	10	210.2	0.057	2.5	1.00
108	Pure	Scratch	11	323.1	0.060	2.6875	1.00
109	Lake	Smooth	1	444	0.049	2.375	1.00
110	Lake	Smooth	2	351	0.058	2.5	1.00
111	Lake	Smooth	3	301.8	0.045	2.46875	1.00

Notes (refer to Test #)

104
- Frozen sideways - UNUSABLE

105
- Slight sideways motion
- Moaning sound after fracture
- Ice chunks on b.s.

106
- Ice fracture at max. force
- Ice chunks on b.s. after fracture

107
- Cracking noises slightly precede max. force
- More ice on b.s. after fracture than previously seen

108
- Cracking precedes max. force
- Ice all over surface
- Residual forces present after fracture

109
- Lot of moaning/cracking
- Ice on b.s. again

110
- Loud moaning sound
- Ice chunks on b.s. after fracture

111
- Same as 110

Ice/Aluminum Bond Tests - 6/27/95
Morning Tests

Temperature - 0°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
112	Pure	Scratch	12	351	0.038	2.5	1.00
113	Pure	Scratch	13	199.8	0.026	2.46875	1.00
114	Pure	Scratch	14	475	0.042	2.625	1.00
115	Pure	Scratch	15	351	0.033	2.5	1.00
116	Lake	Smooth	5	351	0.047	2.4375	1.00
117	Lake	Smooth	6	485	0.062	2.25	1.00
118	Lake	Smooth	7	489	0.040	2.4375	1.00
119	Lake	Smooth	8	351	0.039	2.4375	1.00

Notes (Refer to Test #)

112
- Some ice chunks on surface after fracture
- Little residual forces

113
- Ice cracked, then b.s fracture

114
- Horizontal, parallel stress lines in ice
- Some ice chunks on surface
- Residual forces present

115
- Cracking noise after fracture
- Ice chunks on surface after fracture

116
- Some ice chunks on surface
- Little residual forces
- "Sheet" ice

117
- Moaning sound on fracture
- Ice on surface
- Larger than normal residual forces

118
- Load moaning sound coming from specimen after fracture
- Large ice chunks on surface

119
- Loud moaning sound at fracture
- "Sheet" has become ridges for all of these tests

Ice/Aluminum Bond Tests - 6/27/95
Afternoon Tests

Temperature - 20°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
120	Pure	Smooth	7	-----	-----	-----	-----
121	Pure	Smooth	8	-----	-----	-----	-----
122	Pure	Smooth	9	-----	-----	-----	-----
123	Pure	Smooth	10	-----	-----	-----	-----
124	Pure	Scratch	7	220.0	0.036	2.3125	1.00
125	Pure	Scratch	8	240.7	0.030	2.21875	1.00
126	Pure	Scratch	9	234.0	0.034	2.3125	1.00
127	Pure	Scratch	10	-----	-----	-----	-----

Notes

- ALL TESTS UNUSABLE DUE TO TEMPERATURE (not lowered to correct value)

Ice/Aluminum Bond Tests 6/28/95
Morning Tests

Temperature - 0°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
128	Pure	Scratch	16	351	0.052	2.5	1.00
129	Pure	Scratch	17	412	0.047	2.375	1.00
130	Pure	Scratch	18	-----	-----	-----	1.00
131	Pure	Scratch	19	280.9	0.030	2.625	1.00
132	Pure	Smooth	7	236.0	0.039	2.4375	1.00
133	Pure	Smooth	8	351	0.036	2.46875	1.00
134	Pure	Smooth	9	268.5	0.040	2.4375	1.00
135	Pure	Smooth	10	260.5	0.038	2.5	1.00

Notes (refer to Test #)

128
- Many cracks in ice
- Cracking sounds after fracture
- Ice chunks on surface
- Little residual force

129
- Cracking sound before/after fracture
- Residual forces present
- No chunks on surface (except a little at the top)

130
- Sideways fracture - UNRELIABLE results

131
- Cracking/chipping throughout run
- Ice chunks on surface
- Residual forces after fracture

132
- No residual forces
- Ice crack at time of fracture
- Little ice chunks on b.s.

133
- Loud moaning sound after fracture
- Large residual forces
- Ice chunks ("sheet") on b.s.

134
- Loud moaning after fracture
- Ice chunks on b.s. ("sheet") - not as much as before
- Little residual force

135
- Ice cracking throughout test
- Moaning sound after fracture
- No residual forces

Ice/Aluminum Bond Tests - 6/28/95
Afternoon Tests

Temperature - 20°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
136	Pure	Scratch	11	277.8	0.031	2.375	1.00
137	Pure	Scratch	12	351	0.034	2.375	1.00
138	Pure	Scratch	13	347.0	0.058	2.4375	1.00
139	Pure	Scratch	14	351	0.057	2.4375	1.00
140	Pure	Smooth	11	244.3	0.034	2.4375	1.00
141	Pure	Smooth	12	280.8	0.034	2.5625	1.00
142	Pure	Smooth	13	230.7	0.034	2.5625	1.00
143	Pure	Smooth	14	351	0.034	2.5	1.00

Notes (refer to Test #)

136
- Moaning after fracture
- Ice chunks on surface
- Much residual force

137
- No residual force
- No ice chunks on b.s.

138
- Some moaning
- No chunks on surface

139
- Moaning after fracture
- Very small ice chunks on surface

140
- Moaning sound after fracture
- No ice chunks on surface

141
- Moaning sound after fracture
- No ice chunks on surface
- Much residual force

142
- Moaning sound after fracture
- No ice chunks on surface
- Lots of residual forces

143
- Loud moaning/clicking sound after fracture
- No ice chunks on b.s.
- Lots of residual forces

Ice/Aluminum Bond Tests - 6/29/95
Morning Tests

Temperature - 0°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
144	Lake	Scratch	1	446	0.048	2.625	1.00
145	Lake	Scratch	2	351	0.045	2.375	1.00
146	Lake	Scratch	3	351	0.054	2.375	1.00
147	Lake	Scratch	4	446	0.033	2.5	1.00
148	Pure	Smooth	11	520	0.059	2.375	1.00
149	Pure	Smooth	12	331.6	0.046	2.375	1.00
150	Pure	Smooth	13	-----	-----	-----	-----
151	Pure	Smooth	14	-----	-----	-----	-----

Notes (refer to Test #)

144
- Clean fracture - no ice chunks
- Little residual forces

145
- Very little "cracking"
- Ice chunks on b.s.
- Residual forces present

146
- Slight sideways fracture - QUESTIONABLE results
- Cracking sounds at/after fracture
- Some ice chunks on surface

147
- Cracking at/after fracture
- Ice chunks on surface

148
- Loud moaning after fracture
- Large ice chunks on b.s. ("sheet")
- Residual forces present

149
- Cracking/chipping before max. force
- Some ice chunks on surface

150
- Large crack at b.s. - UNUSABLE

151
- Frozen sideways - UNUSABLE

Ice/Aluminum Bond Tests - 6/29/95
Afternoon Tests

Temperature - 20°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
152	Lake	Scratch	7	-----	-----	-----	-----
153	Lake	Scratch	8	-----	-----	-----	-----
154	Lake	Scratch	9	-----	-----	-----	-----
155	Lake	Scratch	10	-----	-----	-----	-----
156	Lake	Smooth	7	-----	-----	-----	-----
157	Lake	Smooth	8	-----	-----	-----	-----
158	Lake	Smooth	9	-----	-----	-----	-----
159	Lake	Smooth	10	-----	-----	-----	-----

Notes (refer to Test #)

TESTS SCRUBBED BECAUSE SAMPLES WERE NOT FROZEN.

Ice/Aluminum Bond Tests - 6/30/95
Morning Tests

Temperature - 0°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
160	Lake	Scratch	5	317.3	0.026	2.5625	1.00
161	Lake	Scratch	6	490	0.045	2.4375	1.00
162	Lake	Scratch	7	342.2	0.030	2.625	1.00
163	Lake	Scratch	8	351	0.032	2.5625	1.00
164	Lake	Smooth	9	479	0.032	2.4375	1.00
165	Lake	Smooth	10	351	0.024	2.5625	1.00
166	Lake	Smooth	11	305.1	0.027	2.5625	1.00
167	Lake	Smooth	12	317.1	0.034	2.5625	1.00

Notes (refer to Test #)

160
- Ice chunks on b.s.
- Lots of residual forces

161
- Some ice chunks on b.s.
- Little residual forces

162
- Lots of residual forces
- Ice chunks on b.s.

163
- Some residual forces
- Ice cracked at time of fracture
- No ice chunks on surface

164
- Large, knocking sound
- Huge, thick chunks of ice on b.s.
- Large residual forces

165
- Loud knocking sound
- Some ice chunks on b.s.

166
- Ice cracks at fracture
- Loud moaning sound
- Little residual forces

167
- Ice cracks at moment of fracture
- Loud moaning noise after fracture
- Large ice chunks on surface ("sheet")

Ice/Aluminum Bond Tests - 6/30/95
Afternoon Tests

Temperature - 20°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
168	Lake	Scratch	11	351	0.032	2.375	1.00
169	Lake	Scratch	12	274.9	0.039	2.125	1.00
170	Lake	Scratch	13	332.9	0.042	2.3125	1.00
171	Lake	Scratch	14	275.8	0.027	2.375	1.00
172	Lake	Smooth	11	277.4	0.036	2.125	1.00
173	Lake	Smooth	12	276.7	0.049	2.3125	1.00
174	Lake	Smooth	13	351	0.032	2.5	1.00
175	Lake	Smooth	14	333.1	0.038	2.5	1.00

Notes (refer to Test #)

168
- Residual forces present
- Slight moan long after fracture
- Ice chunks on b.s.

169
- "Squealing" sound after fracture
- Some ice chunks on b.s.
- Little residual force present

170
- Squealing sound after fracture
- A few ice chunks on b.s.
- Little residual forces present

171
- Quick fracture
- Very little ice on b.s.
- No residual force

172
- Loud moaning after fracture
- Some ice on surface
- Little residual force

173
- Lots of residual force
- Loud moaning after fracture
- Some ice on surface

174
- Loud cracking sound after fracture
- Some ice on b.s.
- HUGE residual forces (2x as much as before)

175
- Large residual forces
- Some ice on b.s.
- Loud moaning after fracture

Ice/Aluminum Bond Tests - 7/3/95
Morning Tests

Temperature - -10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
176	Lake	Scratch	1	267.6	0.027	2.3125	1.00
177	Lake	Scratch	2	351	0.026	2.3125	1.00
178	Lake	Scratch	3	-----	-----	-----	-----
179	Lake	Scratch	4	342.2	0.029	2.25	1.00
180	Lake	Smooth	1	301.2	0.042	2.4375	1.00
181	Lake	Smooth	2	310.2	0.032	2.3125	1.00
182	Lake	Smooth	3	221.7	0.034	2.375	1.00
183	Lake	Smooth	4	205.3	0.022	2.375	1.00

Notes (refer to Test #)

176
- Ice cracking throughout experiment
- Some residual forces
- Ice chunks on b.s.

177
- Ice cracks before/during/after fracture
- Lots of residual forces
- Very little ice on surface

178
- Sample frozen along side of cup - UNUSABLE

179
- Some residual forces
- Ice cracking throughout experiment
- A few ice chunks on surface

180
- Ice cracking at surface
- Ice chunks on surface

181
- Ice cracking/chipping at fracture
- Large ice chunks on surface
- "Squawking" sound after fracture

182
- Ice cracked sideways - UNRELIABLE

183
- Nothing noteworthy

Ice/Aluminum Bond Tests - 7/3/95
Afternoon Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
184	Lake	Scratch	8	436	0.052	2.375	1.00
185	Lake	Scratch	9	323.2	0.047	2.375	1.00
186	Lake	Scratch	10	292.5	0.050	2.0625	1.00
187	Lake	Scratch	11	293.0	0.037	2.3125	1.00
188	Lake	Smooth	6	326.9	0.037	2.4375	1.00
189	Lake	Smooth	7	-----	-----	-----	-----
190	Lake	Smooth	8	295.1	0.035	2.5	1.00
191	Lake	Smooth	9	297.7	0.035	2.5	1.00

Notes (refer to Test #)

184
- Some ice chipping with fracture
- Some ice chunks on surface
- Residual forces present

185
- Ice frozen unevenly near b.s. (around sides of specimen)
- Ice chunks on surface - uneven chunks

186
- Ice chips at fracture
- Little residual forces
- Few ice chunks on b.s.

187
- Little residual forces
- Some ice chunks on b.s.

188
- Loud moaning after fracture
- Residual forces present
- Some ice chunks on surface ("Sheet")

189
- Procedure Error - UNUSABLE

190
- Slight sideways fracture - QUESTIONABLE results

191
- Loud moaning at fracture
- Residual forces present
- Some ice chunks on surface ("Sheet")

Ice/Aluminum Bond Tests - 7/5/95
Morning Tests

Temperature - -10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
192	Lake	Scratch	5	446	0.048	2.4375	1.00
193	Lake	Scratch	6	490	0.069	2.5	1.00
194	Lake	Scratch	7	520	0.061	2.375	1.00
195	Lake	Scratch	8	351	0.036	2.375	1.00
196	Lake	Smooth	5	618	0.058	2.5625	1.00
197	Lake	Smooth	6	557	0.060	2.375	1.00
198	Lake	Smooth	7	351	0.049	2.4375	1.00
199	Lake	Smooth	8	533	0.051	2.375	1.00

Notes (refer to Test #)

192
- Large ice chunks on b.s.
- Residual forces present

193
- Ice chunks on surface
- Large residual forces

194
- Crack appears at fracture
- Some ice chunks on surface
- Residual forces present

195
- Large ice chunks on b.s.
- Residual forces present

196
- WOW!
- No residual forces due to spring action of ice (although ice was not readily removed from b.s.)

197
- Again, no residual forces for same reason

198
- Loud moaning noise after fracture
- Ice chunks on surface
- Residual forces present

199
- No residual forces
- Ice chipping at fracture

Ice/Aluminum Bond Tests - 7/5/95
Afternoon Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
200	Lake	Scratch	12	282.9	0.033	2.375	1.00
201	Lake	Scratch	13	351	0.029	2.375	1.00
202	Lake	Scratch	14	-----	-----	-----	-----
203	Lake	Scratch	15	288.9	0.027	2.1875	1.00
204	Lake	Smooth	10	235.3	0.044	2.5	1.00
205	Lake	Smooth	11	351	0.042	2.4375	1.00
206	Lake	Smooth	12	351	0.045	2.3125	1.00
207	Lake	Smooth	13	-----	-----	-----	-----

Notes (refer to Test #)

200
- No residual forces
- Ice break at fracture
- Some ice chunks on surface

201
- Ice chipping with fracture
- Ice chunks on surface
- Some residual forces

202
- Slight sideways fracture - UNRELIABLE

203
- Cracking before/during/after fracture
- Little residual forces

204
- Residual forces present
- Loud moaning after fracture
- Some ice chunks on surface ("sheet")

205
- Loud moaning after fracture
- No ice cracking till fracture (same with 204)
- Ice chunks on surface ("sheet")
- Large residual forces

206
- No ice cracking until fracture (see 204/205)
- Loud moaning after fracture
- "sheet" ice chunks
- Residual forces present

207
- Frozen off-center - UNUSABLE

Ice/Aluminum Bond Tests - 7/6/95
Morning Tests

Temperature - -10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
208	Lake	Scratch	6	317.8	0.036	2.6875	1.00
209	Lake	Scratch	7	466	0.052	2.625	1.00
210	Lake	Scratch	8	-----	-----	-----	-----
211	Lake	Scratch	9	-----	-----	-----	-----
212	Lake	Smooth	11	351	0.053	2.5625	1.00
213	Lake	Smooth	12	285.7	0.052	2.6875	1.00
214	Lake	Smooth	13	-----	-----	-----	-----
215	Lake	Smooth	14	273.3	0.033	2.5625	1.00

Notes (refer to Test #)

208
- Quick fracture
- Residual forces present
- Ice chunks on b.s.

209
- Cracking before/during/after fracture
- Ice chunks on b.s.
- Residual forces present

210
- Uneven surface led to sideways fracture - UNUSABLE

211
- Sideways fracture - UNUSABLE

212
- Ice cracking with fracture

213
- Ice chunks on surface
- Little residual forces

214
- Sideways fracture - UNUSABLE

215
- Loud moaning sound after fracture
- Ice chunks on surface
- Little residual forces

Ice/Aluminum Bond Tests - 7/6/95
Afternoon Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
216	Pure	Scratch	19	306.8	0.046	2.5	1.00
217	Pure	Scratch	20	-----	-----	-----	-----
218	Pure	Scratch	21	351	0.046	2.5	1.00
219	Pure	Scratch	22	351	0.051	2.375	1.00
220	Pure	Smooth	18	351	0.057	2.3125	1.00
221	Pure	Smooth	19	-----	-----	-----	-----
222	Pure	Smooth	20	-----	-----	-----	-----
223	Pure	Smooth	21	316.9	0.054	2.4375	1.00

Notes (refer to Test #)

216
- Quick fracture
- Residual forces present
- Some ice chunks on surface

217
- Surface uneven - UNRELIABLE results

218
- No cracking till fracture
- No residual forces due to "hop" displacement

219
- Same as 218

220
- Cracking/chipping before fracture
- Loud moaning after fracture
- Large residual forces
- Ice chunks on surface ("Sheet")

221
- Uneven surface - UNUSABLE

222
- Uneven surface - UNUSABLE

223
- Loud moaning after fracture
- Ice "Sheet" on b.s.
- Little residual forces

Ice/Aluminum Bond Tests - 7/7/95
Morning Tests

Temperature - -10°F

Tests	Water	Sample	#	Force	Disp.	Height	Speed
224	Pure	Scratch	10	315.9	0.034	2.8125	1.00
225	Pure	Scratch	11	317.9	0.031	2.75	1.00
226	Pure	Scratch	12	-----	-----	-----	-----
227	Pure	Scratch	13	-----	-----	-----	-----
228	Pure	Smooth	15	-----	-----	-----	-----
229	Pure	Smooth	16	241.1	0.043	2.6875	1.00
230	Pure	Smooth	17	-----	-----	-----	-----
231	Pure	Smooth	18	-----	-----	-----	-----

Notes (refer to Test #)

224
- Ice chunks on b.s.
- No residual forces

225
- Residual forces present
- Ice chunks on b.s.

226
- Not centered - UNUSABLE

227
- Not centered - UNUSABLE

228
- Not centered - UNUSABLE

229
- Ice fracture in pieces
- Ice chunks on b.s.

230
- Ice cracked up - UNUSABLE

231
- Not centered - UNUSABLE

Ice/Aluminum Bond Tests - 7/7/95
Afternoon Tests

Temperature - 10°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
232	Pure	Scratch	23	232.8	0.054	2.25	1.00
233	Pure	Scratch	24	230.7	0.045	2.375	1.00
234	Pure	Scratch	25	284.1	0.046	2.125	1.00
235	Pure	Scratch	26	-----	-----	-----	-----
236	Pure	Smooth	22	248.5	0.036	2.1875	1.00
237	Pure	Smooth	23	-----	-----	-----	-----
238	Pure	Smooth	24	313.6	0.046	2.375	1.00
239	Pure	Smooth	25	-----	-----	-----	-----

Notes (refer to Test #)

232
- No residual forces
- Few ice chunks on b.s.

233
- Cracking throughout experiment
- Little residual forces
- Some ice chunks on surface

234
- Cracking throughout experiment
- No residual forces

235
- Frozen sideways - UNUSABLE

236
- Loud moaning after fracture
- Large residual forces

237
- Not frozen - UNUSABLE

238
- Loud moaning after fracture
- Ice chunks on surface ("sheet")
- Large residual forces

239
- Frozen sideways - UNUSABLE

Ice/Aluminum Bond Tests - 7/10/95
Morning Tests

Temperature - 0°F

Test	Water	Sample	#	Force	Disp.	Height	Speed
240	Pure	Smooth	13	-----	-----	-----	-----
241	Pure	Smooth	14	351	0.029	2.5625	1.00
242	Pure	Smooth	15	235.7	0.026	2.375	1.00
243	Pure	Smooth	16	244.3	0.029	2.4375	1.00
244	Pure	Scratch	20	281.1	0.030	2.3125	1.00
245	Pure	Scratch	21	351	0.049	2.625	1.00
246	Pure	Scratch	22	475	0.063	2.375	1.00
247	Pure	Scratch	23	351	0.075	2.5	1.00
248	Pure	Painted	1	351	0.033	2.3125	1.00
249	Pure	Painted	2	145.1	0.043	2.3125	1.00
250	Pure	Painted	3	243.1	0.018	2.3125	1.00
251	Pure	Painted	4	275.2	0.033	2.375	1.00

Notes (refer to Test #)

240
- Frozen sideways - UNUSABLE

241
- Ice cracking throughout run
- Ice chipping at fracture
- No residual forces

242
- Loud moaning after fracture
- Some ice chunks on surface
- Little residual forces

243
- Ice cracks on fracture
- Little residual forces

244
- Ice chipping after fracture
- Low residual forces

245
- No residual forces due to "hop" displacement
- Ice chunks on b.s.

246
- Residual forces present
- Ice chunks on surface

247
- Little residual forces
- Ice chunks on surface

248
- Ice chipping on fracture

249
- Multiple ice cracks appear throughout run

250
- Ice chipping on fracture
- No residual forces

251
- Ice cracks before fracture
- No residual forces

APPENDIX B

Results of Data Analysis for Each Condition (Temperature, Surface Modification, and Ice Purity)

Sample Type: Smooth Temperature: 20°F Water Type: Distilled

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	294.1	0.040	3.338	88.11
2	332.5	0.035	3.878	85.74
3	279.6	0.043	3.534	79.12
4	210.4	0.022	3.731	56.40
5	449	0.047	3.731	120.3
11	244.3	0.034	3.829	63.80
12	280.8	0.034	4.025	69.76
13	230.7	0.034	4.025	57.32
14	351	0.034	3.927	89.38
AVG.	--------	-----	---------	78.88 +/- 20.12 (SD)

Sample Type: Scratched Temperature: 20°F Water Type: Distilled

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	351	0.034	3.829	91.67
3	273.3	0.046	3.043	89.81
4	351	0.057	3.780	92.86
5	351	0.032	3.436	102.2
6	320.1	0.033	3.632	88.13
11	277.8	0.031	3.731	74.46
12	351	0.034	3.731	94.08
13	347.0	0.058	3.829	90.62
14	351	0.057	3.829	91.67
AVG.	--------	-----	---------	90.61 +/- 7.26 (SD)

Sample Type: Smooth Temperature: 20°F Water Type: Lake

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	310.5	0.036	4.123	75.31
2	228.7	0.028	4.123	55.47
3	401	0.033	4.123	97.26
5	279.7	0.033	4.123	67.84
6	253.2	0.034	3.878	65.29
11	277.4	0.036	3.338	83.10
12	276.7	0.049	3.632	76.18
13	351	0.032	3.927	89.38
14	333.1	0.038	3.927	84.82
AVG.	--------	-----	---------	77.18 +/- 12.99 (SD)

Sample Type: Scratched Temperature: 20°F Water Type: Lake

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	351	0.031	3.780	92.85
3	445	0.041	4.025	110.6
4	351	0.034	3.976	88.28
5	270.0	0.042	3.927	68.75
11	351	0.032	3.731	94.08
12	274.9	0.039	3.338	82.35
13	332.9	0.042	3.632	91.66
14	275.8	0.027	3.731	73.92
AVG.	--------	-----	---------	87.81 +/- 13.01 (SD)

Sample Type: Smooth Temperature: 10°F Water Type: Distilled

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	441	0.043	3.632	121.4
3	229.9	0.034	3.829	60.04
4	339.2	0.050	3.731	90.91
4	500	0.099	3.731	134.0
5	248.4	0.043	3.632	68.39
9	276.9	0.035	4.025	68.80
10	284.9	0.031	3.829	74.41
11	334.0	0.036	3.829	87.23
12	258.1	0.041	3.731	69.18
14	582	0.049	3.927	148.2
15	252.3	0.047	3.240	77.87
16	288.5	0.040	3.632	79.43
17	183.4	0.032	4.123	44.48
18	351	0.057	3.632	96.64
21	316.9	0.054	3.829	82.76
22	248.5	0.036	3.436	72.32
24	313.6	0.046	3.731	84.05
AVG.	--------	-----	---------	85.89 +/- 26.57 (SD)

Sample Type: Scratched Temperature: 10°F Water Type: Distilled

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
4	500	0.099	3.731	134.0
5	248.4	0.043	3.633	68.37
7	351	0.051	4.123	85.13
8	347.1	0.059	4.123	84.19
9	347.3	0.060	4.123	84.23
10	262.7	0.045	4.123	63.72
11	272.3	0.037	3.534	77.05
12	306.9	0.060	3.731	82.26
13	204.4	0.032	3.829	53.38
14	286.3	0.023	4.123	69.44
16	347.2	0.046	3.731	93.06
17	295.1	0.038	3.927	75.15
18	479	0.049	3.632	131.9
19	306.8	0.046	3.927	78.13
21	351	0.046	3.927	89.38
22	351	0.051	3.731	94.08
23	232.8	0.059	3.534	65.87
24	230.7	0.045	3.731	61.83
25	284.1	0.046	3.338	85.11
AVG.	--------	-----	---------	82.96 +/- 20.79 (SD)

Sample Type: Smooth Temperature: 10°F Water Type: Lake

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	351	0.031	3.731	94.08
2	276.6	0.040	3.829	72.24
3	292.6	0.050	3.731	78.42
4	260.4	0.033	3.731	69.79
5	502	0.049	3.828	131.1
6	326.9	0.037	3.829	85.37
8	295.1	0.035	3.927	75.15
9	297.7	0.035	3.927	75.81
10	235.3	0.044	3.927	59.92
11	351	0.042	3.829	91.67
12	351	0.045	3.632	96.64
AVG.	--------	-----	---------	84.56 +/- 19.06 (SD)

Sample Type: Scratched Temperature: 10°F Water Type: Lake

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	351	0.028	3.878	90.51
2	351	0.037	3.927	89.38
3	351	0.044	3.927	89.38
4	351	0.045	3.731	94.08
5	304.1	0.030	3.534	86.05
8	436	0.052	3.731	116.9
9	323.2	0.047	3.731	86.63
10	292.5	0.050	3.240	90.28
11	293.0	0.037	3.632	80.67
12	282.9	0.033	3.731	75.82
13	351	0.029	3.731	94.08
15	288.9	0.027	3.436	84.08
AVG.	--------	-----	---------	89.82 +/- 10.04 (SD)

Sample Type: Smooth Temperature: 0°F Water Type: Distilled

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	292.2	0.040	4.222	69.21
2	293.2	0.044	4.222	69.45
3	351	0.036	4.320	81.25
4	276.1	0.042	4.222	65.40
5	285.5	0.039	4.222	67.62
6	351	0.032	4.123	85.13
7	236.0	0.039	3.829	61.63
8	351	0.036	3.878	90.51
9	268.5	0.040	3.829	70.12
10	260.5	0.038	3.927	66.34
11	520	0.059	3.731	139.4
12	331.6	0.046	3.731	88.88
14	351	0.029	4.025	87.20
15	235.7	0.026	3.731	63.17
16	244.3	0.029	3.829	63.80
AVG.	--------	-----	---------	77.94 +/- 19.81 (SD)

Sample Type: Scratched Temperature: 0°F Water Type: Distilled

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
2	351	0.034	3.632	96.64
3	351	0.108	4.320	81.25
4	450	0.034	3.927	114.6
6	351	0.037	3.731	94.08
7	242.7	0.032	3.927	61.81
8	311.7	0.072	4.025	77.44
9	299.8	0.054	4.025	74.48
10	210.2	0.057	3.927	53.53
11	323.1	0.060	4.222	76.53
12	351	0.038	3.927	89.38
13	199.8	0.026	3.878	51.52
14	475	0.042	4.123	115.2
15	351	0.033	3.927	89.38
16	351	0.052	3.927	89.38
17	412	0.047	3.731	110.4
19	280.9	0.030	4.123	68.13
20	281.1	0.030	3.632	77.40
21	351	0.039	4.123	85.13
22	475	0.063	3.731	127.3
23	351	0.075	3.927	89.38
AVG.	--------	-----	---------	86.15 +/- 20.18 (SD)

Sample Type: Smooth Temperature: 0°F Water Type: Lake

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	444	0.049	3.731	119.0
2	351	0.058	3.927	89.38
3	301.8	0.045	3.878	77.82
5	351	0.047	3.829	91.67
6	485	0.062	3.534	137.2
7	489	0.040	3.829	127.7
8	351	0.039	3.829	91.67
9	479	0.032	3.829	125.1
10	351	0.024	4.025	87.20
11	305.1	0.027	4.025	75.80
12	317.1	0.034	4.025	78.78
AVG.	--------	-----	---------	100.1 +/- 22.55 (SD)

Sample Type: Scratched Temperature: 0°F Water Type: Lake

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)EEE12h1OFsHCE	AREA OF SURFACE (in.^{2})	STRESS (psi)
1	446	0.048	4.123	108.2
2	351	0.045	3.731	94.08
3	351	0.054	3.731	94.08
4	446	0.033	3.927	113.6
5	317.3	0.026	4.025	78.83
6	490	0.045	3.829	128.0
7	342.2	0.030	4.123	83.00
8	351	0.032	4.025	87.20
AVG.	--------	-----	---------	98.37 +/- 16.84 (SD)

Sample Type: Smooth Temperature: -10°F Water Type: Distilled

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	338.2	0.033	4.025	84.02
2	296.1	0.029	3.927	75.40
3	351	0.028	4.025	87.20
4	260.5	0.035	3.927	66.34
5	201.6	0.029	4.025	50.09
6	198.6	0.029	3.731	53.23
7	256.6	0.027	4.025	63.75
8	192.9	0.057	3.829	50.38
9	261.7	0.031	3.534	74.05
11	351	0.053	4.025	87.20
12	285.7	0.052	4.222	67.67
14	273.3	0.033	4.025	67.90
16	241.1	0.043	4.222	57.11
AVG.	-------	-----	---------	68.03 +/- 13.15 (SD)

Sample Type: Scratched Temperature: -10°F Water Type: Distilled

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
3	304.1	0.059	3.632	83.72
4	209.4	0.045	3.829	54.69
5	247.7	0.060	3.632	68.20
6	317.8	0.036	4.222	75.27
7	466	0.052	4.123	113.0
10	315.9	0.034	4.418	71.50
11	317.3	0.031	4.320	73.45
AVG.	--------	-----	---------	77.12 +/- 18.08 (SD)

Sample Type: Smooth Temperature: -10°F Water Type: Lake

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	ARRA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	301.2	0.042	3.829	78.66
2	310.2	0.032	3.632	85.41
4	205.3	0.022	3.731	55.03
5	618	0.058	4.025	153.5
6	557	0.060	3.731	149.3
7	351	0.049	3.829	91.67
8	533	0.051	3.731	142.9
AVG.	--------	-----	---------	108.2 +/- 39.66 (SD)

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1996	Technical Memorandum

4. TITLE AND SUBTITLE
Shear Strength Analysis of the Aluminum/Ice Adhesive Bond

5. FUNDING NUMBERS
WU-274-00-00

6. AUTHOR(S)
Denis A. Lynch III and Damian R. Ludwiczak

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-10112

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-107162

11. SUPPLEMENTARY NOTES
Denis A. Lynch III, University of Notre Dame, Notre Dame, Indiana 46556; Damian R. Ludwiczak, NASA Lewis Research Center. Responsible person, Damian R. Ludwiczak, organization code 4310, (216) 433-2383.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category Categories 03, 39, and 70

This publication is available from the NASA Center for Aerospace Information, (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The shear strength of an aluminum/ice adhesive bond is analyzed for the purpose of gaining an appreciation for the forces necessary to break this bond. The results of this work have a direct bearing on future attempts to develop de-icing systems for aircraft. Results of testing indicate that system temperature, bonding surface conditions, and ice purity profoundly influence the adhesion strength. An explanation of testing parameters and procedures are presented, along with a detailed characterization of the results and suggestions for further study.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Ice; Adhesive bond; Aluminum	63
	16. PRICE CODE: A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

Sample Type: Scratched Temperature: -10°F Water Type: Lake

TEST NUMBER	FORCE APPLIED (lb_f.)	DISPLACEMENT (in.)	AREA OF SURFACE OF ICE ($in.^2$)	STRESS (psi)
1	267.6	0.027	3.632	73.68
2	351	0.026	3.632	96.64
4	342.2	0.029	3.534	96.83
5	446	0.048	3.829	116.5
6	490	0.069	3.927	124.8
7	520	0.061	3.731	139.4
8	351	0.036	3.731	94.08
AVG.	--------	-----	---------	106.0 +/- 22.13 (SD)

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